The Art of Writing Scientific Papers

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The Art of Writing Scientific Papers

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I. Starting the Process

Generating an Outline: The Classic Scientific Paper Structure

I. Introduction
II. Materials/Methods
III. Results
IV. Discussion/Conclusion

As a first step, type/write in each of these categories at the top of an otherwise blank sheet of paper.

Generating an Outline: A Creative Approach

As a 1-hour exercise, imagine:

What questions is your smart beer-drinking scientist friend (SBDSF) liable to ask you about your work, in conversation over drinks?

The outline generated from your one-to-three-sentence answers to your SBDSF's questions will take the shape of the classic scientific paper.

Starting the “Creative Outline”

Your SBDSF would likely want to know the following:

- What’s the general question or problem being studied?
- Why is this question or problem important?
- How is this question/problem connected to other work in the field?
- What is the specific approach you’re using to study the question/problem?
- What will you argue (What is the “high concept”)?

(The beginnings of an Introduction section)

Now You're on a Roll! Your SBDSF is getting interested.

- What materials/methods am I using, and how would I use them?
- How long would I do X (a certain experimental action or process)?
- How many times do I do X to obtain a result?
- How would I repeat this experiment (or go about constructing this model)?

(The beginnings of a Materials/Methods section)

The Roll Continues!

- What was the experiment or simulation performed?
- What were the essential conditions?
- How did the experiment or simulation turn out—give details! (This one might require a few more sentences.)

(The beginnings of a Results section)

Now You’re Beyond a Roll

- **What do the results indicate?**
- **What is the significance of the results?**
- **How are they connected to results from other scientists?**
- **How might the results be wrong?**
- **Do you have problems** (related to this project!)**?**
- **How would you handle them?**
- **Now what? What next?**

(The beginnings of a Discussion/Conclusion section)

YOUR 1-3 SENTENCE ANSWERS TO ALL THESE QUESTIONS WILL HELP ORGANIZE YOUR THOUGHTS AND GENERATE CONTENT, WHILE RETAINING A CONVERSATIONAL TONE.

NOW LET’S FOCUS ON YOUR INTRODUCTION

First Sentence

The first sentence must be short and sweet…

Keep the first sentence of your paper concise. The first sentence should quickly orient your reader, clearly informing him or her in 25 words or less, what your general subject matter is. **And then it should end!**

…but it must also avoid the obvious!

"Geological carbon sequestration has been an important research topic for the last two decades."

"The universe is a large place."

The High Concept

- The “high concept” (a term borrowed from the film industry) is a clear, one-sentence encapsulation of what your paper is about.
- It is useful in organizing and unifying your writing.
- It makes the reader want to keep reading.
- It works as a confirmed hypothesis.

Why High Concept?

The high concept should be part of the introduction because:

The earlier the reader gets a sense of the **whole**, the easier it is for the reader to assimilate the **parts**, as these parts accrue in the process of reading.

Sample High Concepts

- *Slithering freely at 20,000 feet, poisonous snakes terrify airline passengers and feed into the audience's deepest fears.*

- *We aim to validate existing transport models and generate new models for gaseous reactants through microporous layers, using various gas-diffusion layer types and saturation levels.*

- *We have integrated the FE-I4 chip within the prototype Time-Projection Chamber (TPC), thus achieving higher ATLAS pixel-detector performance.*

Write an Introduction That Ends the Suspense

1. **Orientation**—(First sentence) Start with orienting the reader—What is the general subject that you're talking about (e.g., geothermal energy)? Remember, short and sweet—without insulting your reader's intelligence!

2. **Statement of the Problem/Issue/Context**—1-X paragraphs (depending on length)—What question or problem confronts you? Provide a context for what you say in your paper. This part typically includes a literature review to convey the state of science in relation to the problem—for example, developing enhanced geothermal energy systems. Within the literature review, compare previous papers to identify knowledge gaps and formulate the objectives for your paper.

3. **Statement of what you're focusing on in your paper, how you'll proceed (agenda), and the High Concept**—one paragraph—In the beginning of the last introductory paragraph, present your agenda in the paper (what you will talk about and perhaps how you will talk about it) and state your paper's high concept. (What is your solution, or your contribution to existing knowledge?)

In your introduction, tell your whole story in a broad, simple way.

A Sample Introduction

The resource base for geothermal energy is enormous, but exploitation of this renewable resource is currently limited to hydrothermal systems, within which naturally present fracture networks permit fluid circulation and allow geothermal heat to be produced by tapping these hot fluids through wellbores. Most geothermal resources occur in rock that lacks fracture permeability and fluid circulation. “Enhanced” or “engineered” geothermal systems (EGS) aim to extract geothermal energy from these resources.

Previous attempts to develop EGS have all employed water as a heat transmission fluid (Lippman et al., 2002). Water has many properties that make it a favorable medium for this purpose, but it also has serious drawbacks. Several recent studies have found that injecting water into hot rock fractures causes strong dissolution and precipitation effects that change fracture permeability and make it very difficult to operate an EGS reservoir in a stable manner (Xu and Pruess, 2004; Blair et al., 2006; Cummings, 2007)…

Cognizant of water’s limitations, Brown (2008) proposed using carbon dioxide (CO_2) instead of water as a heat transmission fluid, with geologic sequestration of CO_2 as an ancillary benefit....

The present paper extends Brown’s theoretical work by using computer/ numerical modeling to compare the thermophysical properties of CO_2 and water, and examining pressure and temperature conditions for the flow of CO_2 in wellbores. We also compare the flow behavior of CO_2 with the flow behavior of water, to identify both the favorable and unfavorable characteristics of CO_2 as an EGS working fluid. Our findings show that an EGS system running on CO_2 has sufficiently attractive features to warrant further investigation.

Instructions for Interactive Exercise: Introduction

- Groups have ten minutes to:
  - Read the sample introduction independently
  - Agree on a spokesperson
  - Evaluate/agree as a group whether the introduction met the standards described on page 15. If the introduction works, why?
    - First sentence short and to the point?
    - Problem/question/issues/context clearly described?
    - Agenda and high concept included & effectively stated?

- Spokespersons briefly summarize their group's conclusions.

II. Writing the Thing

- **Write before you feel ready.**
- **Limit your editing at this stage. Write quickly**—don't get bogged down on any one issue. If you're having trouble with one section, go on to the next.
- **Write for your SBDSF (or for your mother)**—keep it conversational.

III. Editing for Your Reader: No One Gets It Right the First Time

It’s Not about You: Your SBDSF Puts on an Editing Uniform

1. **Individual Sentences**
   (Controlling Complexity, Preserving Clarity)

2. **Sentences in Context**
   (Writing Paragraphs with Focus, Coherence, and Emphasis)

A General Editing Trick

- 1. Read your first draft aloud (perhaps to your SBDSF?)

Individual Sentences: Who's Doing What?

- The temperature was initially set to 4ºC. (*simple sentence*)
- Attempting to achieve these conditions, the temperature was initially set to 4ºC, while holding the methane gas pressure at 4.8 MPa. (*complex sentence, with a problem*)
- Attempting to achieve these conditions, **[our modeling group? modelers? scientists? investigators? the authors? we?]** initially set the temperature to 4ºC, while holding the methane gas pressure at 4.8 MPa. (*complex sentence, fixed*).

Individual Sentences: Who's Doing What, Continued

Within a sentence:

- Make sure that the subject of a sentence follows soon after any introductory modifier, and that it (the subject) can do what the modifier says it can do.

- Prefer active voice.

- Put verb as closely as possible to the subject.

Finding Subject and Verb, Bringing Them Together

- The assumptions that all sites evolve at one evolutionary rate, that this rate is uniform across the genome, that sites evolve independently, and that the phylogenetic models have the same substitution patterns all represent oversimplifications of the sequencing process.

- In assuming that…patterns, …

- Many investigators assume that…patterns. These all….

Sentences in Context (Paragraphs): Focus and the Topic Sentence

- Most paragraphs contain a *topic sentence* that comes at the beginning of the paragraph (first or second sentence).
- The topic sentence announces the central idea of the paragraph and limits what follows in the paragraph to that central idea. [“Each unit of discourse should make a single point”]
- The topic sentence imposes unity (focus) on the paragraph. (Avoid monster paragraphs!)
- The topic sentence should *tend* to be short.

Sentences in Context (Paragraphs): Cohesion through Connective Tissue (Identity and Transition)

- Sentences at the beginning of a paragraph *and* within a paragraph should contain *connective tissue*.

- This connective tissue can consist of signals of *identity* or *transition* that refer back to the previous sentence, so that the reader can easily see the kind of relationship that's implied between one statement and the next one.

Signals of Identity and Transition

Signals or terms of *identity* assert that something already treated is still under discussion. These terms are usually pronouns (*he, she, it*), repeated words and phrases, or demonstrative adjectives (*this, these, that, those*) that are understood in the light of the previous sentence.

Signals or terms of *transition* indicate *how* a statement will build on the previous one. For example:

Time or Place: *later, earlier, then, here, there, at the same time, above, below*
Consequence: *therefore, thus, as a result, consequently*
Likeness: *likewise, similarly*
Contrast/reversal: *but, however, nevertheless, on the other hand, yet*
Continuation/Amplification: *again, in addition, furthermore, moreover, also*
Example: *for instance, for example*
Sequence: *first, second, third…, finally*
Recapitulation: *in conclusion, to summarize, in summary*

Such signals needn't appear in every sentence, but they become useful whenever the relationship between two sentences wouldn't be immediately clear without them—as is the case fairly often in science writing!

Sentences in Context: Transitions and Emphasis

- In a complex sentence, what comes last is most emphatic.

- Your reader expects the material *at the beginning of a sentence* to provide a connection backwards to already established material. They expect the material *at the end of a sentence* to be new and informative—so if at all possible, put such material there!

- Beginnings of sentences should ideally contain *connective tissue*—a signal of identity or transition or repeated terms—providing a bridge between the previous sentence and the new, important information to come later in the present sentence. That new material is *emphasized* by the structure of the sentence—it's the punch line!

A Sample Main Body Paragraph

Similarly, when we look at flow rates, the potential advantages of a system using CO_2 rather than water become clearer. For high temperatures, flow rates for such a system are found to be ~50% larger than for water, a very substantial acceleration of energy recovery. CO_2 flow rates are in fact larger than for water by a factor of ~3.7 initially, and decrease less over time than water flow rates. For low temperatures, the viscosity of water increases much more than that of CO_2, giving CO_2 an additional advantage for flow in the vicinity of the injection well. We can conclude, from this analysis, that much of the advantage of CO_2 is due to enhanced mobility at the lower temperatures prevailing near the injection well.

Instructions for Interactive Exercise: Main Body Paragraph

- Read the paragraph (3 minutes).
- Find a partner.
- Discuss whether the paragraph includes an effective topic sentence and stays on track (i.e., focused).
- Identify the terms of coherence (identity and transition) within the paragraph.
- Discuss whether the paragraph appears to have effective emphasis (i.e., do we seem to learn something new towards the end of sentences?).

Report back to Dan!

3. Checking Your Conclusion: Tying It All Together

- *Synthesize* (bring together) your high concept and your key results—For the conclusion's topic sentence, include a statement that paraphrases or echoes your high concept; then *immediately* reiterate, in encapsulated form (bullets?), the findings that support the high concept.
- Significance of your results/findings—what does it all mean?
- *Reorient* your reader, indicating how things have changed (or could change) in light of your results. Or remind the reader of what you didn't talk about, what was outside the scope of your discussion, or how some results suggest other possibilities, indicating the need for further research.

CO_2 Paper Conclusion

The specific findings of our modeling studies show that EGS driven by CO_2 holds considerable promise. These findings can be summarized as follows:

- Due to its much larger expansivity and compressibility as compared to water, supercritical CO_2 will generate much stronger buoyancy forces between injection and production wells. This will reduce power consumption for the fluid circulation system and would allow adequate fluid circulation without external pumping.
- CO_2 will generate on the order of four times larger mass flows and larger heat extraction rates compared to water.
- Whereas the loss of water in a “conventional” (water-driven) EGS operation would be disadvantageous and costly, fluid loss in an EGS system running with CO_2 would offer the possibility of geologically storing this greenhouse gas.

As we mentioned earlier, the heat-extraction and wellbore-dynamics studies pertain to what may be called “fully developed” EGS reservoirs, operating with either CO_2 or water as heat transmission fluid. We did not address the very important question of how such a reservoir would actually be created, focusing instead on the comparative heat-extraction efficiencies of fully developed water-based and CO_2-based EGS. For the practical feasibility and success of EGS-CO_2 development, the process of displacing water and replacing it with injected CO_2 will obviously be a crucial step to be explored in future studies.

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Instructions for Interactive Exercise: Conclusion

- Read the conclusion (3 minutes).
- Discuss with Dan whether the conclusion succeeds. If the conclusion is lacking, identify what the issues are.
    - Does the conclusion include a summary of the important results?
    - Does it indicate the significance of its results, reorienting the reader with respect to larger scientific issues?
    - Does it suggest its own limitations and possibilities for further research
    - Do the conclusions support the high concept?

IV. Finishing It Off—Abstract

The Abstract: Worth Your Tender Loving Care

- Most people (including editors and reviewers) will read your paper only if your *abstract* interests them.
- In terms of market reached, the abstract is the most important part of the paper—for every *one* person who reads your entire paper, from *10 to 500* will read the abstract.
- An abstract is an abbreviated representation of the paper *containing in itself the essential information* of that paper—it can stand alone, independent from the paper.
- The abstract typically selects a highlight(s) from each section of the paper, covering the main information in the paper in a single paragraph.
- It contains the answer to your research question/purpose (i.e., it contains a rewording or paraphrase of your high concept).
- A good one avoids general statements that merely hint at results or act like a rough table of contents.

Signals for the Abstract

- Question/Purpose/Method:
  "To determine whether…, we…"
  "We asked whether…."
- Results
  "We found…"
  "Our results show…"
  "Here we report…"
- Answer/Conclusion
  "We conclude that…"
  "These results confirm (or conflict with) …"
  "Thus…."
- Implication (So What?)
  "These results further suggest…"
  "These results may be important for…"
  "Our findings have significant implications for…"

CO_2 Paper Abstract

- Responding to the need to reduce atmospheric emissions of carbon dioxide, Brown (2000) proposed a novel enhanced geothermal system (EGS) concept that would use carbon dioxide (CO_2) instead of water as heat transmission fluid, achieving geologic sequestration of CO_2 as an ancillary benefit. To determine the validity of Brown's proposal, we used numerical simulation to evaluate the fluid dynamics and heat-transfer issues in an engineered geothermal reservoir that would be operated with CO_2. From our evaluations, we found that CO_2 offers certain advantages, especially with respect to wellbore hydraulics, in that its larger compressibility and expansivity compared to water would increase buoyancy forces and reduce the parasitic power consumption of the fluid circulation system. Given these findings, it seems clear that while major uncertainties remain with regard to chemical interactions between fluids and rock, the thermal and hydraulic aspects of a CO_2-EGS system warrant further investigation.

Takeaways

- Invent an SBDSF to ask you questions related to your paper.
- Keep first sentence short and sweet.
- Generate a high concept (don’t leave your intro without one!).
- Within every sentence, make sure the reader knows who is doing what (or make sure that it doesn’t matter!).
- Provide sufficient transition between paragraphs *and sentences* to ensure that the reader can follow your argument.
- Write and edit with your reader (SBDSF) in mind—*empathy*.